Instrumentation Experiences
Power Systems Development Facility

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Sensors and Controls for Power Plants, SIcon 2001

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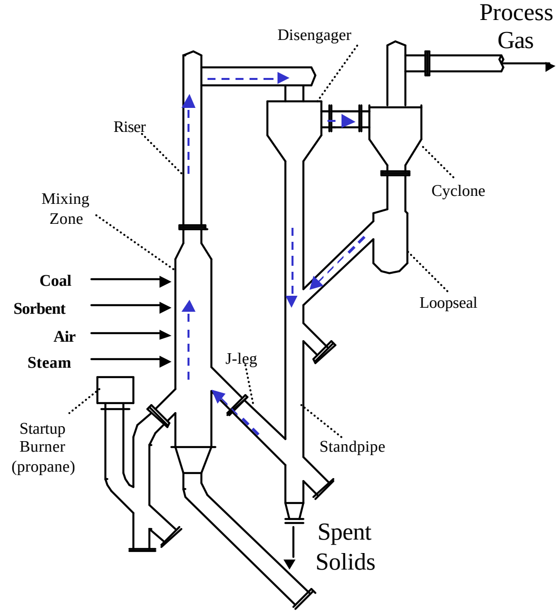
The Power Systems Development Facility (PSDF) is an engineering scale demonstration of advanced coal-fired power systems and high-temperature, high-pressure gas filtration systems. While filling a need to test advanced power systems and components in an integrated fashion, the PSDF is of sufficient size to provide data for commercial scale-up. The PSDF is funded by the U. S. Department of Energy, the Electric Power Research Institute, Southern Company, Kellogg Brown & Root, Inc., Siemens Westinghouse Power Corporation, and Peabody Holding Company.

A primary focus of the PSDF is to demonstrate and evaluate high-temperature, high-pressure particulate collection devices (PCDs), an important component required for successful development of advanced power generation systems. The Transport Reactor, which supplies gas to the PCDs, is an advanced circulating fluidized bed reactor designed to operate as either a pressurized combustor or a gasifier. The reactor operates at considerably higher circulation rates, velocities and riser densities than a conventional circulating bed, resulting in higher throughput, better mixing, and higher mass and heat transfer rates.

Advantages of a Pressurized Transport Reactor

- Excellent Gas-Solids Contact
- Low Mass Transfer Resistance Between Gas and Solids
- Highly Turbulent Atmosphere
- High Coal Throughput
- High Heat Release Rate
- Designed Without Expansion Joints



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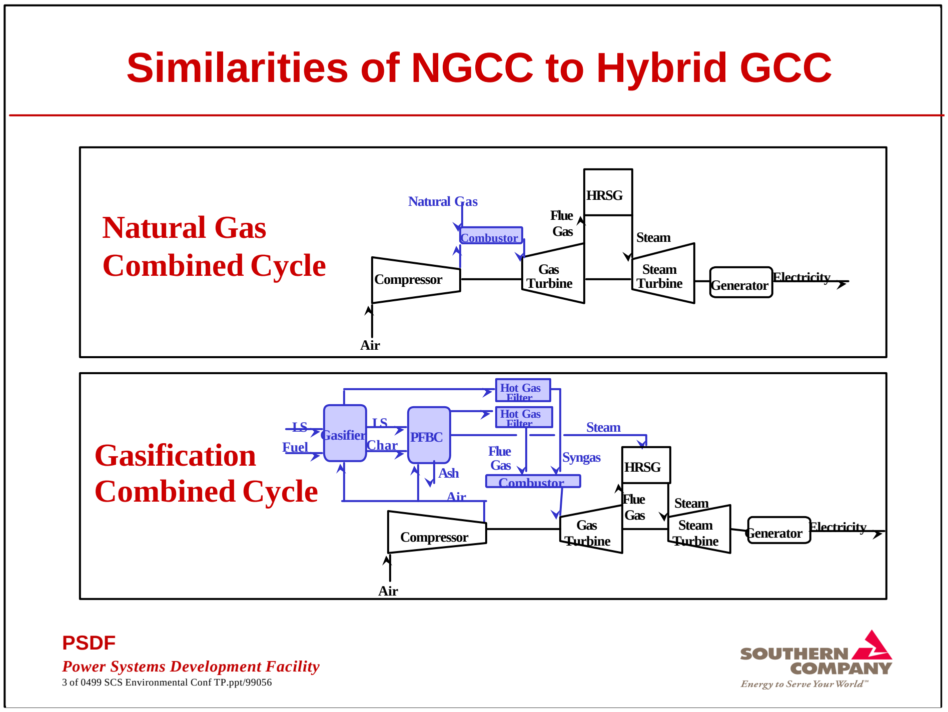
The Transport reactor, configured as a gasifier, consists of a mixing zone, riser, disengager, cyclone, standpipe, loop seal, and J-leg. Fuel, sorbent, steam, and air are mixed together (fuel rich) in the mixing zone, along with recirculated solids from the standpipe. The gas with entrained solids moves up from the mixing zone into the riser. Temperatures increase from 1600 to 1825°F, some char is combusted releasing heat. Remaining char is converted to CO and then to CO_2 & H_2 during steam gasification. Temperatures in the riser section fall a little as coal is devolatized, completing the creation of synfuel. The riser which has a slightly smaller diameter, makes two turns and enters the disengager. The disengager removes larger particles by gravity separation and then most of the remaining particles are removed in the cyclone. The solids collected by the disengager and cyclone are recycled to the mixing zone through the standpipe and J-leg.

The Transport reactor was operated in combustion mode for approximately 5000 hours from 1996 - 1999 at a typical operating condition of 1625°F and 200 psig. Reconfigured for synfuel production, the Transport reactor began operation as a gasifier in September 1999. Over 1900 hours of gasification have been achieved to date with three different fuels. Gasification was carried out at temperatures of 1600 to 1825°F and pressures of up to 240 psig, with coal flow rates of 2,500 to 6,000 pounds per hour. Synthesis gas heating values of 80-120 Btu/SCF, coal carbon conversions over 90%, and hot gas efficiencies over 85% have been achieved.

Excellent gas-solids contact in both the horizontal and vertical directions in the reactor is attributed to the high mass flux. Flow is highly turbulent in the reactor due to the high gas velocity and high entrained solids content. With the excellent gas-solids contact and highly turbulent regime, there is minimal mass transfer resistance between the gas and solids. This low resistance promotes high carbon conversions resulting in high coal throughput and high heat release rates. Its design, without expansion joints, simplifies construction, reduces cost, and improves reliability.



Similarities of NGCC to GCC

Hybrid Gasification Combined Cycle utilizes much of the Natural Gas Combined Cycle technology but allows for the combustion of a coal derived synthetic fuel instead of natural gas. A conceptual plant design and cost estimate were completed for a commercial power system design using the transport gasifier. Major design bases were as follows:

<u>Gasifier</u>

•air-blown transport gasifier at 400 psia and 1800°F, 95% carbon conversion
•dry feed of low sulfur Powder River Basin sub-bituminous coal to gasifier
•sorbent injection into gasifier to control sulfur
•syngas filter operates at 750°F with sintered metal candles

<u>Combustor</u>

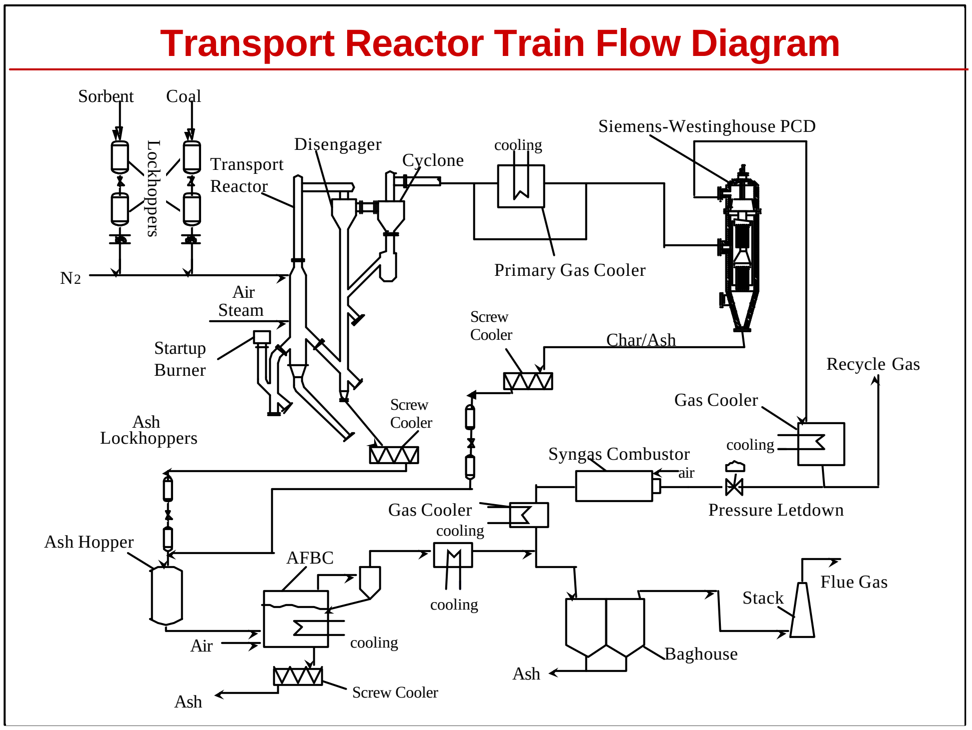
•air-blown transport char combustor at 350 psia and 1600°F, >99.9% carbon conversion vitiated air filter operates at 1000°F with sintered metal candles
•clean vitiated air produces power through a hot gas expander/generator

<u>Combined Cycle</u>

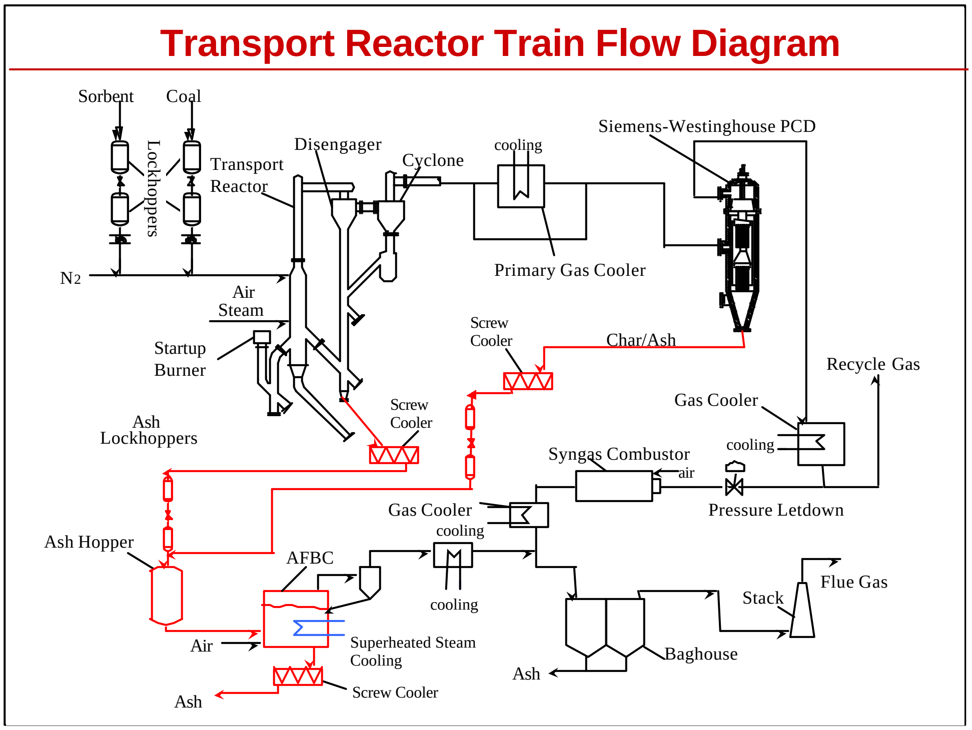
•one modified GE 7FA gas turbine flat-rated at 197 MW by varying extraction air flow
•process air supplied by a gas turbine extraction (boosted) and a supplementary air compressor
•steam is generated in HRSG and by cooling syngas, vitiated air, and combustor solids
•steam cycle conditions: 1820 psia / 1000°F / 1000°F
•combined cycle designed to operate on natural gas as a backup fuel
•Selective Catalytic Reduction system in the HRSG to reduce NOx emissions

Performance of this system was calculated to be 298.4 MW net power, with a heat rate of 8,292 Btu/kW-hr (HHV) during normal operation at average annual ambient conditions. When operating on the backup fuel, the system generates 280.9 MW at a heat rate of 7,943 Btu/kW-hr (HHV).

Capital costs of the system are based on a typical Greenfield southeastern United States location. The all-included capital requirement for the system is $414.7 million (± 20%), which is $1390/kW. This cost was increased by the conservative approach taken in using only near-term commercially available equipment and a relatively small 1 x 1 combined cycle configuration.[1]



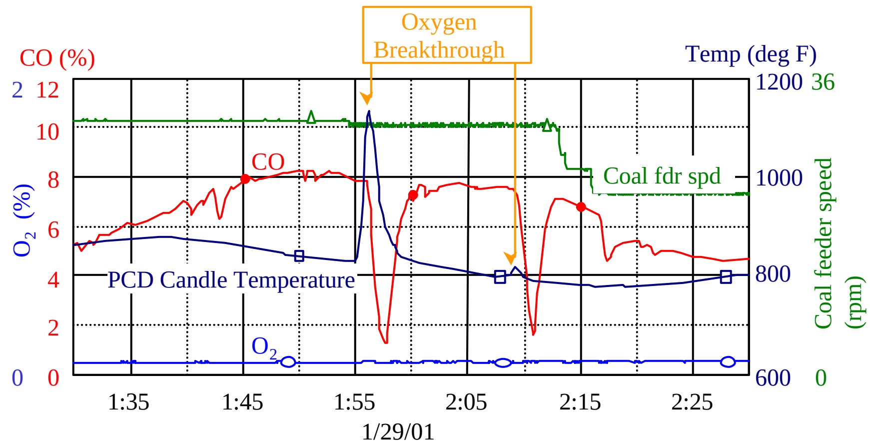
The Transport gasification system includes the feed, waste solids, and gas systems. The fuel and sorbent are separately fed into the Transport gasifier through lock hoppers. The gas leaves the Transport reactor cyclone and passes through the primary gas cooler to the Siemens-Westinghouse PCD barrier filter, where ceramic or sintered metal candles filter out the dust. The PCD removes almost all the dust from the gas stream (to less than 1 part per million) to prevent erosion of a downstream gas turbine in a commercial plant. The operating temperature of the filter is determined by the gasifier temperature and the fraction of gas flow that bypasses the primary gas cooler. At typical gasifier temperatures, the PCD gas temperature can be controlled from 700 to 1,600°F by varying the bypass flow from zero to 100 percent. The filter candles are back-pulsed by high-pressure nitrogen at a fixed time interval or at a specified maximum pressure difference across the candles. A secondary gas cooler after the filter vessel cools the gas before it is discharged through a pressure let-down valve to the syngas combustor. The synthesis gas is sampled for on-line analysis both before and after the secondary gas cooler. In the syngas combustor all of the reduced sulfur compounds (H_2S, COS, CS_2) and reduced nitrogen compounds (NH_3, HCN) are oxidized.[1]



The Transport gasifier produces a fine char/ash mixture that is collected by the PCD and a coarse char/ash mixture that is extracted from the Transport reactor standpipe. The two solid streams are cooled using screw coolers, depressurized in lock hoppers and then combined. The fuel sulfur captured by sorbent is present as calcium sulfide (CaS). The gasification char/ash mixture is combusted in an atmospheric fluidized bed combustor (AFBC) to oxidize the calcium sulfide to calcium sulfate ($CaSO_4$) and burn the residual carbon in the ash. The solids from the AFBC are then suitable for commercial use or disposal. Flue gas from the AFBC is combined with flue gas from the syngas combustor, sent to a baghouse, and then sent to the stack. The AFBC recovers the char/ash carbon heat content as superheated steam. [1]

Why Coal Flow Measurement ?

- Predict Oxygen Breakthrough
  - Coal/No-Coal
  - 2 second Response
- Automatic Coal Feed Control
  - Load Change Stability
  - Process Upset Recovery



Instantaneous coal flow metering was recognized as essential for automating the KBR Transport Reactor for preventing oxygen breakthrough and continuous coal feed. Oxygen breakthrough occurs when the process shifts from oxygen lean gasification to oxygen rich combustion. Temperatures spike from the resulting flash-fire, breaking the filters in the PCDs, and warping thermowells in the reactor. While preventing oxygen break-though was the primary and instigating need for a coal flow measurement, continuous metering is needed to maintain stability during process setpoint and load changes. For oxygen breakthrough prevention an overall metering response time of 2 seconds was considered maximum to prevent a catastrophic fire in the PCD.

Mass Flow Measurement for Coal

- **Velocity** of the coal directly within the pipe
  - Without interference from the transport gas
- Coal **Mass** passing the measurement section
  - Without interference from non-combustible components
- Pressurized Pipe, 350 psi Design
- 1800 °F Reverse Flow Consideration
- 1.25" Double-Extra Strong Pipe (0.9" I.D.)
- Metered Dilute Phase Flow
- Commercial Gasifier Considerations - 450 psi, 3” Pipes

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It was desirable that the unit be truly mass-flow measuring, determining the coal velocity directly and the quantity of coal passing through the instrument.

The unit had to survive momentary reverse flows from the reactor at 1600°F & 350 psi without breaching the pressure boundary. In addition to the reverse flow withstand requirements the measurement technology had to be suitable for application to 1.25-inch double extra-strong pipe (0.9-inch inside diameter) and metered dilute phase flow of 830 pph nitrogen to 5700 pph coal at a transport velocity of 40 f/s. The high transport gas velocity keeps the coal moving rather than sluffing down the pipe.

For commercial applications the flowmeter should be adaptable to 3-inch pipes carrying 40 t/h at 40 f/s without sluffing in the pipe.

Coal Flow Measurement
Plausible Techniques

- Electrostatic/Capacitive (EPRI)
- Microwave
  – With Vortex Transport Gas Flowmeter
  – Without Vortex Transport Gas Flowmeter
- Acoustic
- Nuclear Densitometer + Vortex Flowmeter

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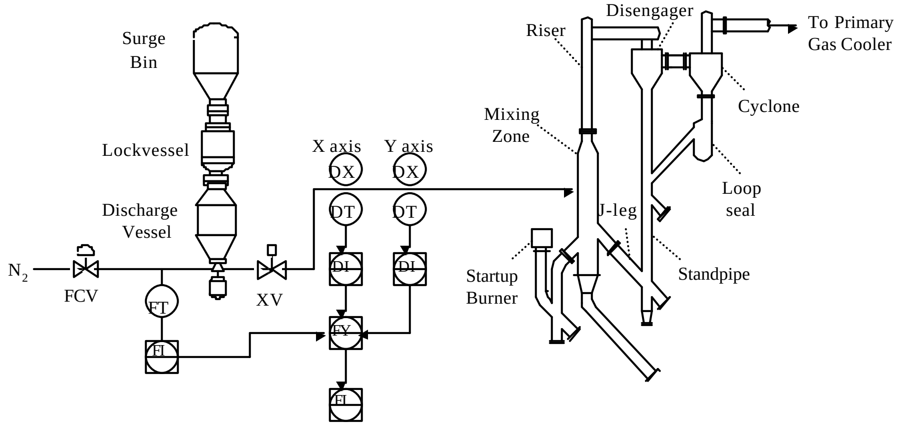
The technologies considered for this application were electrostatic, microwave, acoustic, and nuclear. Non-invasive methods were favored due to the erosive nature of high velocity coal particles. Electrostatic was eliminated because of previous experience with an ambient pressure capacitive device. Microwave was not ready for deployment as a non-invasive technology and had temperature and pressure limitations relative to reactor reverse flow. Acoustic was eliminated based on our experiences with two systems tested at this site. Nuclear was the only remaining non-invasive option. Of the nuclear densitometer vendors contacted only one pursued the application for our small pipe size.

Nuclear based Flowmeter Schematic



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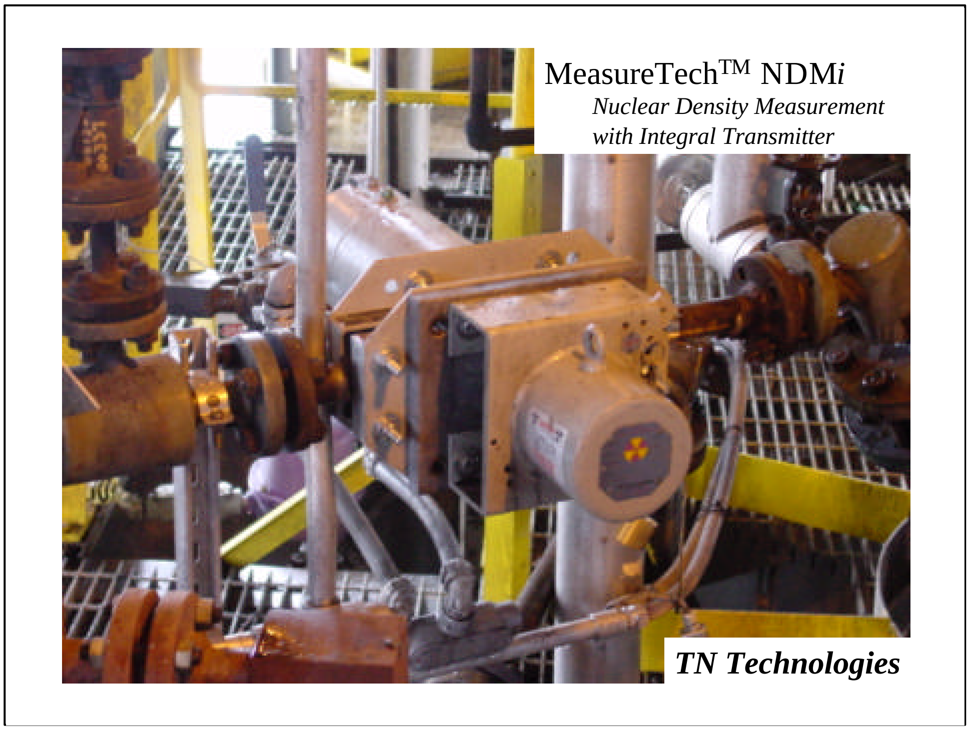
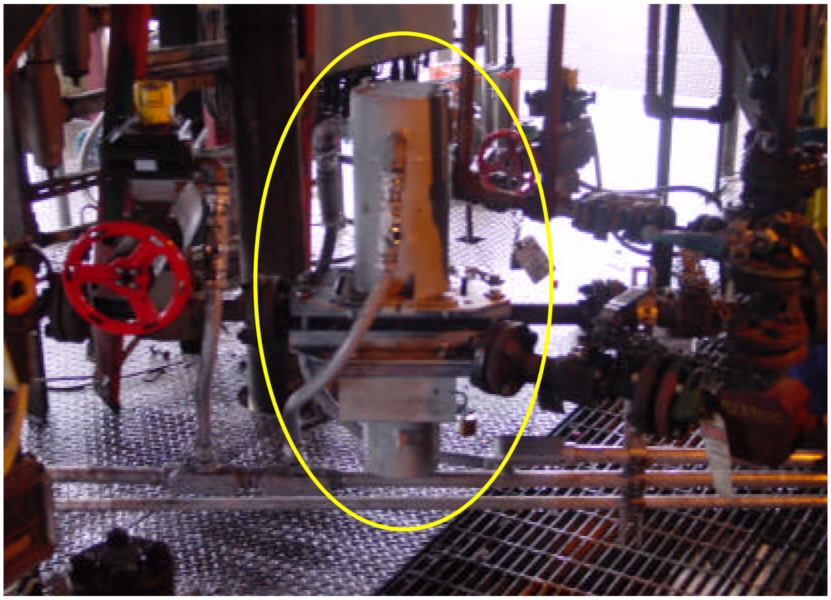
Two nuclear densitometers and the existing coal transport gas flowmeter provided the sensor inputs needed to determine coal flow. One densitometer was installed horizontally and the other in the vertical to improve measurement accuracy and to provide saltation information in addition to average density. Saltation is the settling of solids in the pipe.

Measuring density is only part of the measurement, coal velocity is also needed for the mass-flow calculation. An assumption is made that the coal velocity closely approximates the velocity of the transport gas, as measured by the transport gas vortex flowmeter. The coal velocity will be less than the transport gas velocity in the fluid stream since the transport gas is accelerating the coal. The lower coal velocity is offset somewhat by the volume displacement caused when the coal is added to the gas stream.



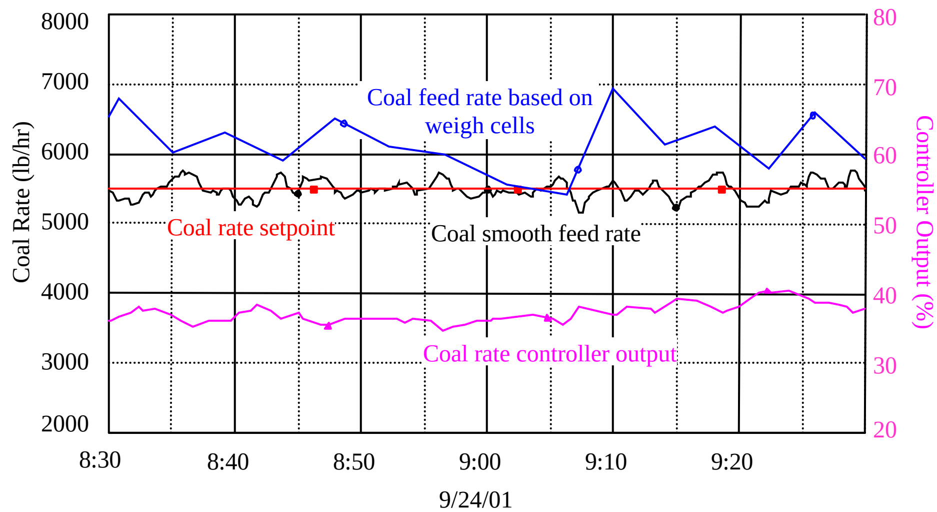
The nuclear densitometer selected was the MeasureTech NDMi, formerly TN Technologies. This unit utilizes a 50 milli-curie source and a scintillation detector suitable for small pipe diameters.



This slide shows the vertical installation in the coal feed line to the reactor. At this time a purge flow enters the stream between the horizontal and vertical densitometers downstream of the vortex meter. Some measurement uncertainty is introduced by this and some existing abandoned piping, disturbing the flow profile. Modifications are underway to eliminate the flow disturbances.

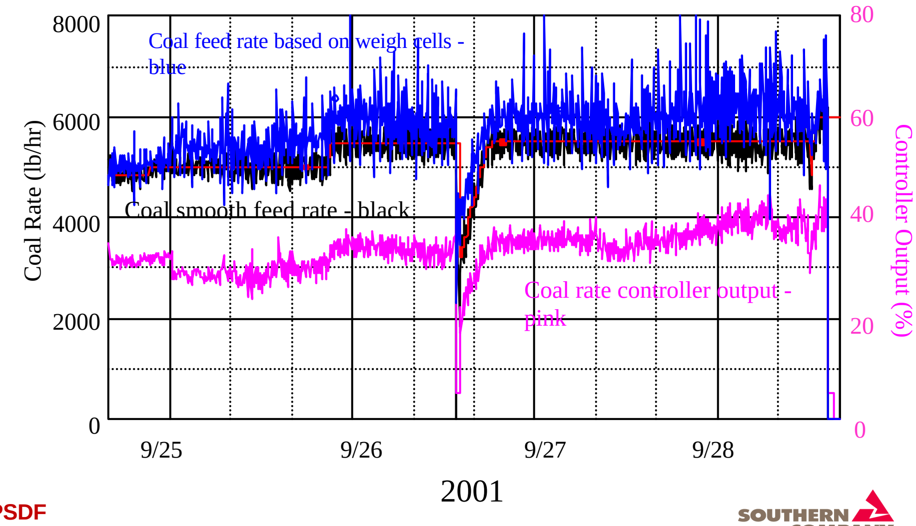
Flow Calculation Considerations

- Density Variations
- Slip Variations



Considerations associated with this mass-flow scheme are; 1) the coal velocity will be less than the transport gas velocity (slip), and 2) densitometers measure the density of the carrier gas along with the coal. The carrier gas density can be 20% of the overall density for low coal flow conditions, so dynamic compensation of the density signal is needed when operating the reactor over wide pressure ranges. A biasing factor is best used to relate the transport gas velocity to the coal particle velocity via a batch weight measurement system. Although the coal feeder was designed as a dilute phase system, no saltation or settling was expected, however, divergence at times of the density readings from the two probes indicate that some saltation was occurring. Note the difference between the batch measurement from weighcells and the smoothed (dampened - 15 sec.) coal flow rate at a setpoint of 5500 lb/hr.

Four Day Trend



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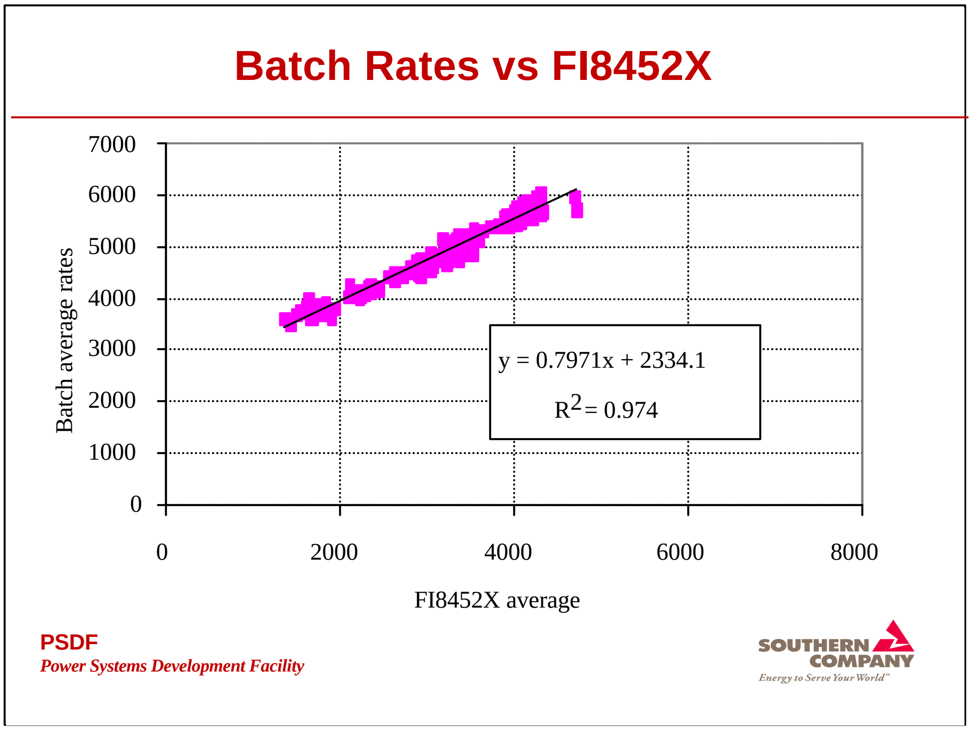
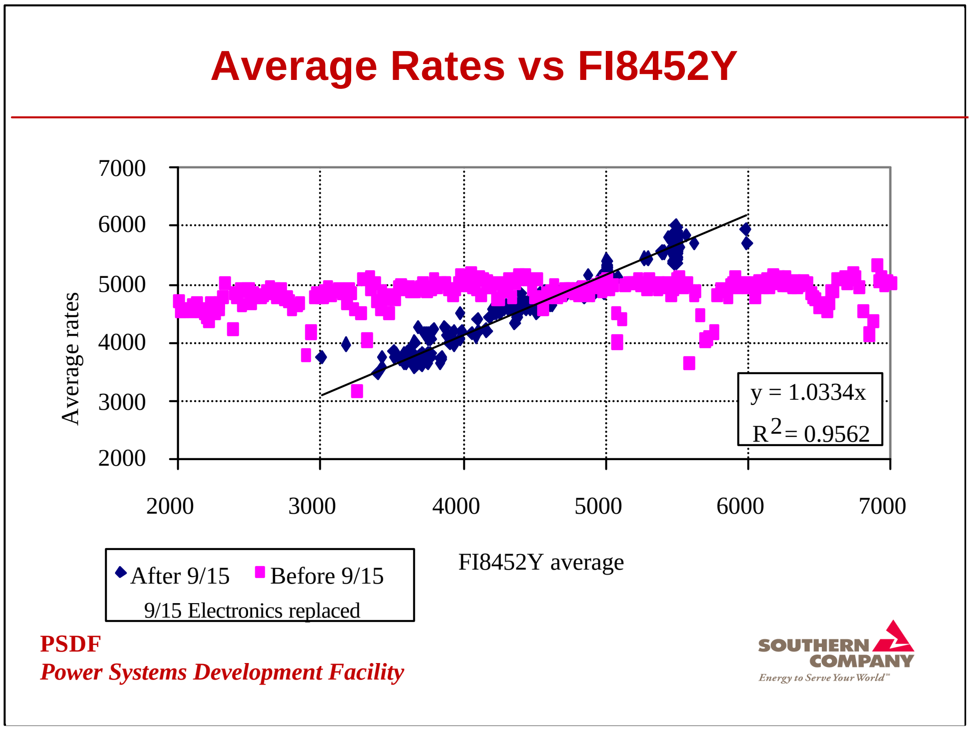
The four-day trend shows how the selected densitometer tracks the batch weight measurement and is consistent with feeder speed demand, even through coal feeder trips.



The batch coal weight system and the horizontal coal flowmeter disagree by a factor and an offset, attributable to issues with calibration. What is important is the repeatability of the system.



The vertical densitometer correlates well to the batch weigh system even with its vibration repeatability issues, which show as scatter in the graph. The data points shown in pink are from the faulty electronics which were replaced 9/15/01. Although the electronics were replaced, issues remain, bumping the housing will cause the densitometer output to change slightly. This unit will be returned to the manufacturer for repair.

Performance

- Recalibration needed before each run.
- Horizontal and Vertical measurements diverged.
- Variability noted with changes in reactor pressure.
- Continuous realignment against batch measurement needed.

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Currently densitometers are recalibrated before each run. Some of the calibration issues are attributable to lack of familiarity with this model and confusing calibration instructions. Training from the manufacturer and a refined calibration procedure should help to improve results.

There has been a need to adjust the slip factor based on the batch weight measurements observed during a run. Some error was noticed when the reactor pressure was changed from the 200-psi calibration point and, expectedly, the density of the transport gas changed. Variability may also be introduced from gas density fluctuations and the coal-grind size since both influence slip velocity.

Further testing is needed to determine individual error contributions from gas density and the coal-grind size. With a refined calibration procedure, further testing, and subsequent control software enhancements the nuclear based mass-flow system should provide acceptable mass flow measurements for the purposes of detecting loss of coal feed and controlling coal feed rate. The ultimate solution to coal mass flow measurement may be a refined microwave based system that measures coal particle velocity and coal mass directly.

Level Measurement for Ash

- Ash Lockhopper Level
- Ash Density
  - 10-20 lb/ft^3
- Pressure Varies
  - 0-240 psig
- Temperature Varies
  - 15-450°F
- Very Low Dielectric Constant

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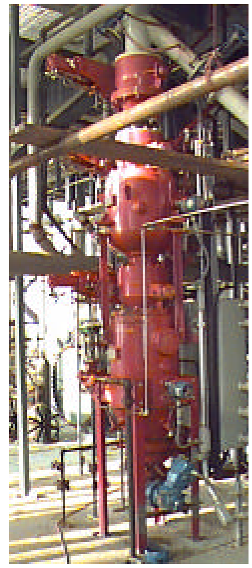

Another difficult application issue at the PSDF has been measuring the level of hot dry coal ash in the lock hoppers of the ash high-pressure letdown system. The low pressure ash letdown system does not have the same reliability issues as the high pressure system. As of this time no suitable instrument has been found for triggering a conveying cycle, so timers are used instead.

Capacitance point level probes have been tested and have failed to detect level reliably in the highly pressurized system. The ash from this process is fluffy, having a density of 10-20 lb/ft^3, and has a low dielectric constant. Dielectric constant is a unit expressing the degree of non-conductivity of different materials. The dielectric constant of a full vacuum is defined as 1.0, Teflon has a dielectric constant of 2.0, cold water about 80, and hot fluffy dry ash about 1.5-2.2. Also, the dielectric constant varies as the lock hoppers pressurize and depressurize, and as the temperature and moisture content varies.

Technologies Considered

- Capacitive - Failed
- RTD - Failed
- Nuclear - Cost prohibitive
- Vibrating Rod or Fork - Temperature too high
- Paddle-wheel - Pressure, channeling issues
- Point Level Radar - Not developed yet

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A specially designed RTD based on a heat absorption technique unit also failed to detect a covered condition properly when placed under pressure. A nuclear densitometer technique with pressure compensation was considered too complex and costly. Vibrating fork and vibrating rod rely on piezoelectric crystals imbedded in the insertion assembly. These crystals limit the temperature range of the instrument to the 275-300°F range, thus are not suitable for this application. A rotating paddle-wheel device was considered, but pressure limitations, the possibility of ash channeling, and maintainability issues were discouraging. One technology that may provide a reliable, cost effective measurement is in a yet to be developed point-level wave-guided radar unit. One vendor has expressed interest in pursuing such a device.

Process Conditions for Thermowell Selection

- Maximum Temperature
  - 2200 °F
- Pressure
  - 240 psi operating
  - 350 psi design
- Temperature ranges from 1580 to 1775 °F
- Erosion
  - High Velocity Sand and Char, Coal Ash
- Reducing Environment
  - Hydrogen Sulfide

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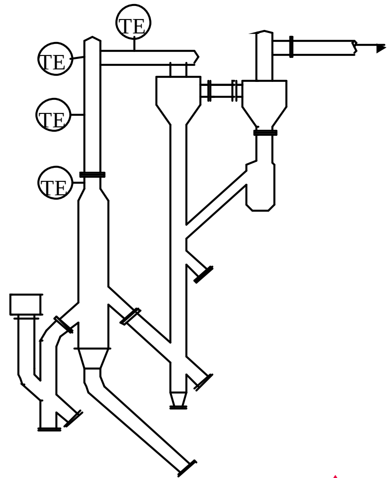
Direct temperature measurements in the Transport Reactor at the PSDF are desirable to diagnose and understand the operation of the developmental system. A commercial system would not necessarily need direct temperature measurement nor measurement in all the locations of the current PSDF Transport Reactor. For a commercial system the thermowells could be pulled nearly flush with the refractory to provide an estimate of stream temperature or measurements downstream of the cyclones could be utilized to provide necessary estimates of reactor temperatures.

Thermowell selection for direct measurement is challenged by the high velocity char and sand particulate, the reducing atmosphere with the presence of hydrogen sulfide, and high temperatures of up to 2200 F at a 350 psig design. (The temperature profile in the Transport Reactor in the gasification mode typically varies from 1580 to 1775 F, but will run higher with bituminous coal and petroleum coke.

Temperature Measurement

- Critical for Transport Reactor
- Need a 10,000 hour minimum life for TW
- Wear on TW depends on location



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While there are several approaches for temperature measurement, direct measurement in the flow stream yields the most accurate information but subjects the thermowells to excessive wear from the riser to the reactor crossover. Direct measurement in the flow stream is the method used thus far at the PSDF. For a commercial system where plants schedule outages once a year, the minimum acceptable themowell life is about 10,000 hours.

To date direct measurement thermowells in these harsh locations of the Transport Reactor have achieved an average life of no more than 1500 hours. Thermowells in the most severe location, the reactor crossover, have not lasted a complete 250-hour run. The slightly less severe locations at the bottom of the riser and just before the turn to the crossover exhibit wear after multiple runs

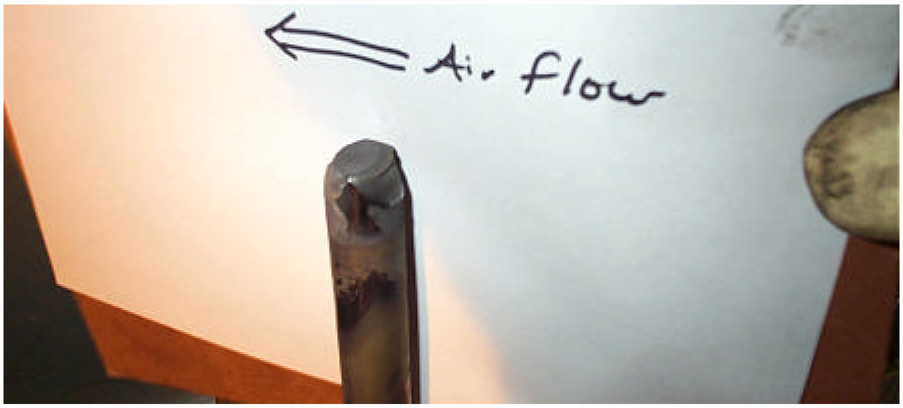
Initial thermowells were made of 304 stainless steel with a gradual taper from 7/8 inch to 0.625 inch diameter, with a 2 inch coating of Wallex 50/55 at the tip. (Wallex 50/55 is a cobalt nickel matrix alloy with tungsten carbide particles.) They did not last more than a few days.

Further investigation resulted in the testing of two new thermowells. A ½ inch full length ceramic tube with Inconel inner shell, and 7/8 to .625 diameter inch tapered 304 stainless steel with 2 inches chrome carbide at the tip. The ceramic tube cracked, the chrome carbide tips eroded away, and both were attacked by hydrogen sulfide.

Thermowell - Before Crossover

The next thermowells tested were 7/8 inch diameter 446 stainless steel with the final five inches of the stem reduced to 0.625 inch diameter. A ceramic sleeve was provided on the upstream side (180 degrees) for the entire length of the stem to shield it from erosion. The ceramic material cracked in places along the stem, however the thermowell was protected where the ceramic was intact.

Middle of Riser



Another notable test was done using 7/8 inch diameter 446 stainless steel full-length construction without the ceramic half-sleeve. These thermowells were robust and survived runs except in the most demanding location. Turning the thermowells one-quarter turn between test runs increased the life to 1500 hours.

Thermowells Summary

446 stainless, 0.62 inch diameter with ceramic sleeve	Ceramic cracked	Most promising with more development
446 stainless 7/8 inch diameter full length	Shows some wear	• Rotate after each run • Dispose of after 4 runs
Ceramic tube with Inconel inner shell	• Ceramic cracked • H2S in the synfuel attacked the Inconel	Failed to last one run
Inconel with 2 inch Chrome Carbide at tip	H2S in the synfuel attacked the Inconel	Failed to last one run
304 stainless tapered 7/8 to 0.625 inch w/2 inch coating of Wallex 50/55	Failed	Lasted only a few days

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So far the 7/8 inch diameter full-length 446 stainless steel thermowells have provided the best service in the harsh locations. They were rotated one quarter turn after each run to even the wear.

The 446 stainless steel thermowells with ceramic sleeve provided excellent service where the ceramic remained intact. The well life could be extended by enlarging the ceramic half sleeve and using a ceramic less prone to cracking.

The other materials did not perform sufficiently to warrant continued development.

To Be Tested

- SS446 with improved ceramic shield
- HR160
  - – Ni-Co-Cr-Si Alloy
  - – High Temperature
  - – Corrosion Resistance
  - – Coal Fired Boilers, Sulfur Furnaces, Cement Kilns

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Future testing of 446 stailness steel will be done with better ceramics.

Another material to be tested is HR160, which has been applied in coal fired boilers, sulfur furnaces, and cement kilns. This material is a nickel-Cobalt-Chromium-Silicon alloy with good high temperature and corrosion resistance. A test thermowell of 7/8 inch diameter 446 stainless steel with a two inch HR160 tip is planned for the reactor crossover.

Other approaches such as recessing the thermocouple into the refractory, out of the direct flow path of the solids, would greatly reduce or eliminate thermowell wear, but would provide an estimated temperature of the flow stream. This would need to be tested to determine if such an approach would be suitable for commercial applications.

Gas Analysis

- Insitu Gas Analysis
  - Fast response
  - Least Loss of Gas Constituents
  - Maintainability
- Extractive
  - Response (1-2 minutes)
  - Requires Reflux Probe

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Gas analysis is needed to gain an understanding of the gasification process performance utilizing various types of coal, limestone, and operating parameters. At PSDF both extractive and in-situ systems are installed to gain experience with the capabilities and limitations of each technology. In-situ systems provide faster, near instantaneous, response where extractive systems are taking 1-2 minutes due to sample transport delay, from the sample point to the analyzer house. Analyzing gas constituents at the point of sampling ensures a more representative analysis of the gas since there is less opportunity for gas composition to change. While in-situ is the preferred analysis technique, high pressure and temperature in-situ systems are not available, nor is there a way to clean the probe should it become plugged. An extractive solution to our gas analysis equipment would require maintaining the sample at 600°F from the inlet, through the analyzer, and from the outlet of the analyzer to the stack. We know of no such system.

Extractive systems in use at PSDF condition the sample prior to analyzer introduction. Any components that would condense out of the stream at the analyzers normal operating temperature are removed by a sample conditioning or chiller unit. When some of the sample is condensed, a fear is other components of the gas stream may be captured as well. For that component, i.e. sulfur, an in-situ measurement is utilized.

Process Gas Composition

N_2, CO, CO_2, H_2, H_2O, CH_4, C_2+, O_2, NH_3, H_2S, HCN, COS, CS_2, HCl, HF, C_6H_6, $C_{10}H_8$

Process Conditions at Sample Location:

1-230 psig, 400-800°F

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Water in the gas stream interferes with the infra-red (IR) measurement of many of the constituents listed here. Naphthalene detrimentally interferes with the ultra-violet (UV) measurement method of hydrogen sulfide (H_2S). So far no vendor has recommended making this measurement. Vendors are saying measuring H_2S with a gas-chromatograph (GC) in the 200-400 ppm range would produce marginal results.

R&R Technologies Reflux Probe

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Until recently tars and other by-products of gasification, such as naphthalene, were causing gas sampling problems by plugging the probes and sample lines. Once optimum operating conditions were realized and understood, process modifications were made to eliminate tar production. Naphthalene, a by-product of gasification, is a problem for gas-analysis, not for a commercial gasification process.

As previously mentioned, extractive systems require gas conditioning prior to analysis. After experiencing significant plugging of probes and sample tubing, a reflux probe, similar to those used in ethylene plants, was installed to remove and return the any tars and naphthalene to the process. The reflux probe is installed vertically. Gas passes upward through double block valves, through a section that causes naphthalene and any tars to fall back into the process.

Heat Exchanger Section

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The cleaned gas continues upward into the sample conditioner shell cooling from 550 to 60°F as it flows around the heat exchanger fins and out the top. Instrument air is utilized as cooling medium, however, to optimize the probes performance a glycol chiller unit will be added.

Inadequate Cooling

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On warm summer days the air cooling is inadequate, naphthalene and other crystals grow on the heat exchanger fins. The other crystals include acenaphthene, anthracene, fluoranthene, and pyrene with boiling points ranging from 190 to 707°F, melting points ranging from 177 to 313°F at operating conditions.

Outlet Filter

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Crystal growth occurs all the way through the reflux cooler system on the hot summer days. On cooler days crystal deposits are minimal. The accumulation of crystals is not a problem for the process, only for the gas conditioning and analysis equipment.

Cooling Tube Ports

Outlet

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There are three U-tubes for the cooling fluid. A barrier separates the inlet section from the outlet. Notice the crystal growth on the heat exchanger outlet.

Developmental Needs

- True Coal Flow Mass Flowmeter
- High Temperature and Pressure Gas Analysis
- Suitable Thermowells
- Level Probes for Hot Dry Coal Ash

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- •True Reading mass flowmeter for Coal Measurement
- •In-situ High Temperature/Pressure Gas Analysis
- •Extractive High Temperature Gas Analysis
- •Suitable Thermowells
- •Point Level Probe for Fluidized Hot Ash at Varying Pressures

End of Presentation

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